

## EXPLORING CORONAL DYNAMICS: A NEXT GENERATION SOLAR PHYSICS MISSION WHITE PAPER

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## ABSTRACT

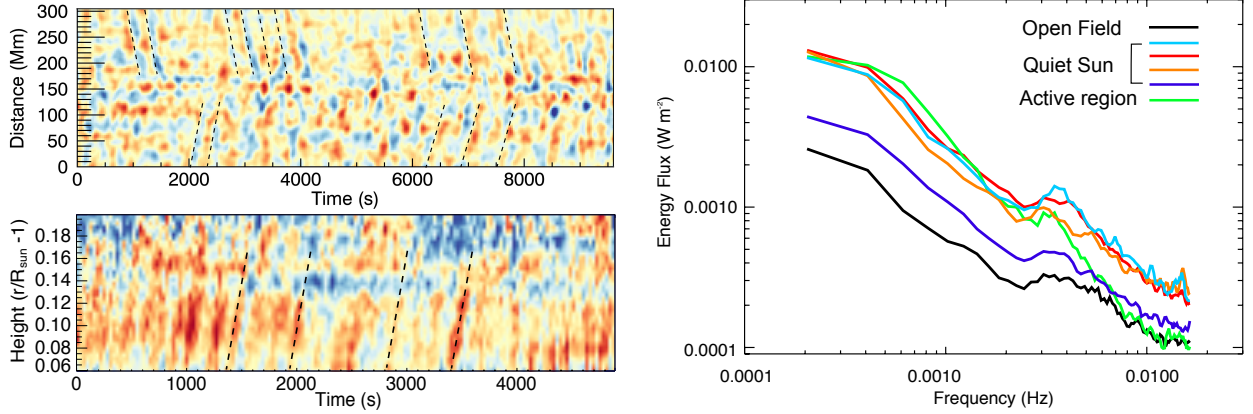
Determining the mechanisms responsible for the heating of the coronal plasma and maintaining and accelerating the solar wind are long standing goals in solar physics. There is a clear need to constrain the energy, mass and momentum flux through the solar corona and advance our knowledge of the physical process contributing to these fluxes. Furthermore, the accurate forecasting of Space Weather conditions at the near-Earth environment and, more generally, the plasma conditions of the solar wind throughout the heliosphere, require detailed knowledge of these fluxes in the near-Sun corona. Here we present a short case for a space-based imaging-spectrometer coronagraph, which will have the ability to provide synoptic information on the coronal environment and provide strict constraints on the mass, energy, and momentum flux through the corona. The instrument would ideally achieve cadences of  $\sim 10$  s, spatial resolution of  $1''$  and observe the corona out to  $2 R_{\odot}$ . Such an instrument will enable significant progress in our understanding of MHD waves throughout complex plasmas, as well as potentially providing routine data products to aid Space Weather forecasting.

## 1. INTRODUCTION

The goals of understanding the physical mechanisms behind coronal plasma heating and solar wind acceleration are still pertinent. This is due to the potential for different mechanisms, e.g., wave dissipation, turbulence, magnetic reconnection, instabilities, to contribute by varying amounts to the energy flux of geometrically distinct magnetic regions (i.e., active regions, closed quiescent loops, open field lines). Recent international interest in the forecasting of Space Weather has added a fresh impetus for making progress in the problems of heating and wind acceleration. In particular, the ability to make predictions of both slow and fast solar wind stream properties, and understanding their variability, are key aspects for determining particle fluxes into the near-Earth environment (and heliosphere) and a contributor to the evolving kinematics of coronal mass ejections through the heliosphere.

Recently, a potential basal contribution to the energy budget has been identified in imaging and spectroscopic observations and interpreted in terms of Alfvénic wave energy (Tomczyk et al. 2007, McIntosh et al. 2011, Thurgood et al. 2014). Alfvénic waves have long been assumed to play a significant role in plasma heating, since their incompressible nature enables them to transfer energy over large distances. Their potentially significant role in determining the nature of the solar wind has long been known, with observations of Alfvénic fluctuations observed from early in-situ measurements (Belcher & Davis 1971) and the Alfvénicity of the fluctuations evident over many frequency decades (periods from seconds to days - e.g., Bruno & Carbone 2005). The *Coronal Multi-channel Polarimeter* (CoMP) was the first instrument to provide evidence for the Alfvénic wave energy flux through the solar atmosphere (Tomczyk et al. 2007), and subsequent investigation has revealed the ubiquity and persistence of this wave flux in Doppler velocities (Tomczyk & McIntosh 2009; De Moortel et al. 2014; Morton et al. 2015, 2016). However because CoMP is ground-based, the afforded observing window only allows for measurements of three frequency decades (seconds to an hour, Fig 1).

These observations have come in conjunction with some success in producing a heating of coronal plasma from wave-driven models (e.g., Suzuki & Inutsuka 2005; Cranmer et al. 2007; Evans et al. 2009) along with reproducing some of the basic properties of slow and fast solar wind. However, there are a number of challenges that these models have to overcome (Cranmer 2009, Ofman 2010), requiring more stringent observational constraints on the mechanisms for delivering energy, mass and momentum (EMM) into the source regions in the low corona. Moreover, current forecasting models employ empirical techniques that have provided relative levels of success (Lee et al. 2009), although they are limited in their predictive power due to the neglect of the physical mechanisms ultimately responsible for plasma heating and wind acceleration. For example, the Wang, Sheeley & Arge (WSA) model relies upon a static, potential coronal field and an empirical formula to estimate wind speed, while the Magnetohydrodynamics-Around-a-Sphere



**Figure 1.** Measurements of the Fe XIII (1074.7 nm) line reveal a wealth of propagating, quasi-periodic features in Doppler velocities throughout the solar corona, which follow the magnetic field and are interpreted in terms of Alfvénic waves. A basic result reveals somewhat balanced counter-propagating Doppler velocity signals in coronal loops (top left panel) and a more uneven, predominately outward propagating signals along open field regions (bottom left panel). The right hand panel shows an estimate for the relative rates of Alfvénic wave energy flux for different magnetic regions in the corona (modified from Morton et al. 2016).

(MAS) model generates a wind by adding an ad-hoc heating function. Successful advancement of our knowledge of the underlying physics and improving forecasting abilities will depend on the accuracy of determining the EMM fluxes through different magnetic regions, quantifying the relative contributions of the plethora of potential mechanisms and detailed knowledge of the free energy in the coronal magnetic field.

Initial results from CoMP have shown promise for synoptic imaging-spectroscopy of the extended corona to contribute to our understanding of the nature and evolution of the coronal magnetic field and associated dynamics. Such an instrument has significant advantages over slit spectrometers (e.g., *Hinode* EIS) that can only provide focused observations of portions of the corona, and also over synoptic imagers (*Solar Dynamic Observatory* (SDO) Atmospheric Imaging Assembly (AIA)) that only provide broadband intensity measurements. In particular, recent CoMP results demonstrate the capability to make unique insights into global behaviour of Alfvénic wave phenomena through the solar corona (Figure 1), with the potential to constrain key features of models, e.g., wave excitation & damping/mode conversion; Alfvénic turbulence; relative energy fluxes through distinct regions of the corona; energy flux from the lower solar atmosphere to the solar wind (Tomczyk & McIntosh 2009; Verth et al. 2010; De Moortel et al. 2014; Morton et al. 2015, 2016). Additionally, CoMP has demonstrated imaging-spectrometer coronagraphs have the potential for the exploitation of waves through magneto-seismology, in combination with spectroscopic techniques, to determine local plasma conditions, e.g., measurements of the plane-of-sky component of the magnetic field and propagation angle with respect to the solar surface. Furthermore, this combination can also provide estimates of the outflow of plasma low in the corona (Morton et al. 2015), which potentially allows for constraints to be placed on EMM fluxes along open-field lines and could also contribute to the identification of regions contributing to the slow solar wind.

CoMP has demonstrated the potential for imaging-spectrometer coronagraphs to reveal unique insights into Alfvénic waves and the ability to constrain their contribution to coronal heating and wind acceleration, but there are some things unachievable by ground-based observations. For example, ground-based instruments will be unable to provide the necessary extended sequences of observations required to probe the Alfvénic waves over the broad frequency range observed out in the solar wind. Additionally, ground-based instruments will also be unable to provide the coverage necessary for continual forecasting of Space Weather due to seeing, weather and the day-night cycle.

## 2. SCIENCE GOALS

The following provides only a small selection of potential science and operational questions that could be answered by a space-based imaging-spectrometer coronagraph. They are mainly focused on the study of wave phenomenon and energy transfer via Alfvénic waves. However, a coronagraph would also be able to contribute to many further science questions surrounding dynamics and ejecta in the corona, e.g., Coronal Mass Ejections (Tian et al. 2013).

1. What are the key physical mechanisms contributing to coronal heating in different magnetic geometries?
  - (i) What is the relative Alfvénic wave energy flux through different magnetic regions?
  - (ii) What are the physical rates for energy deposition by Alfvénic waves in the solar corona?
  - (iii) Is there evidence for the development of Alfvénic wave turbulence in the lower corona?

2. What is the role of Alfvénic waves in the acceleration of the solar wind?
  - (i) What is the evolution of these waves between the solar corona and the solar wind?
  - (ii) How does the Alfvénic wave energy flux vary over the course of the solar cycle?
3. Which regions are key contributors to solar wind streams?
4. Is it feasible to exploit MHD waves via magneto-seismology to provide routine and meaningful characterisation of the plasma and magnetic field conditions in the corona?

### 3. REQUIREMENTS & JUSTIFICATION

*Observables:* In order to make progress in answering the above science questions, a number of diagnostics are required. The envisaged capabilities and observables of a space-based imaging-spectrometer draw directly from the heritage of the CoMP instrument, although technology from other imaging spectrometers will also be valuable. CoMP has been making routine measurements of the 1074.7 nm (Fe XIII) line, taking images at three wavelength positions (1074.50 nm, 1074.62 nm, 1074.74 nm) with a 0.13 nm FWHM filter bandpass. Imaging data products are provided with a 30 s cadence and a spatial sampling of 4.46'' over a 1.05-1.3  $R_{\odot}$  field of view. While the spatial, temporal and spectral sampling are relatively coarse compared to other ground- and space-based instruments, the data products still reveal a wealth of coronal dynamics in the line profile diagnostics, e.g., line core intensity, Doppler shifts, line widths (e.g., [http://mlso.hao.ucar.edu/mlso\\_data\\_COMP\\_2016.php](http://mlso.hao.ucar.edu/mlso_data_COMP_2016.php)). This, coupled with the large synoptic FOV, has enabled unique insights into the global evolution of the coronal magnetic field and coronal Alfvénic waves.

The suitability of the Iron XIII infra-red emission lines for probing coronal physics has been discussed in a number of papers, e.g., [Judge \(1998\)](#) and demonstrated by CoMP. The infra-red Iron line is spectrally broad enough to allow sampling across the line profile, as opposed to narrower EUV coronal lines. In addition, the ability to observe the 1074.7 nm and 1079.8 nm Fe XIII line pair has proved particularly beneficial. The line pair is density sensitive and has enabled co-spatial and co-temporal estimates of the coronal electron density, a key diagnostic for understanding EMM fluxes.

Ideally, increasing the spatial, temporal and spectral resolution of the instrument, compared to CoMP, would prove beneficial. An instrument with similar throughput and sensitivity to CoMP would benefit from the lower noise and scattering afforded by being space-based, permitting improvements in each of these areas. The benefit of higher cadences (5 – 10 s) and spatial sampling ( $\sim 1''$ ) would allow a much finer sampling of the coronal dynamics, extending the range of phenomenon that can be studied, e.g., study of the higher-frequency Alfvénic waves glimpsed in both SDO/AIA and the High-resolution Coronal Imager ( $\sim 60$  s - [Morton & McLaughlin 2013](#); [Thurgood et al. 2014](#)). This would also avoid the under-resolution of the spectroscopic diagnostics from line profiles currently found in the CoMP observations (affecting Doppler velocities and line widths, e.g. [McIntosh & De Pontieu 2012](#)), enabling increased accuracy and sensitivity for wave measurements (demonstrated in EIS wave studies - [van Doorselaere et al. 2008](#)). Additionally, finer spectral sampling would allow for an improvement in the uncertainties of spectral line profiles. And finally, a larger FOV out to 2  $R_{\odot}$  would also provide a significant increase in capability, enabling the evolution of dynamics and ejecta through the low corona to be studied.

*Why observations must be done from space?:* Current data sets from CoMP suffer from various restrictions due to being taken from the ground, and there would be significant benefits from placing a similar instrument in space. Current ground-based observations are subject to a narrow time window before seeing conditions become an issue, with only few data-sets achieving lengths of 3 hours, which hampers the study of events over long time-scales (e.g., Alfvénic waves over extended frequency ranges). Major constraints also exist on when data can be taken and the quality of taken data due to weather conditions and pollutants in the atmosphere. These factors then restrict the capability to provide daily data products required for Space Weather monitoring and forecasting, and also creates problems for long term studies of the evolution of the EMM fluxes over the solar cycle.

In addition, Earth's atmosphere also creates significant problems, with variable seeing conditions and increased scattering of photons leading to lower signal to noise ratios. Furthermore, atmospheric absorption lines also pose problems for accurate photospheric continuum measurements, which are a critical part of the data preparation. As such, these issues have meant that CoMP has not been able to provide routine measurements of large coronal holes or the extended corona due to poor signal to noise, despite having the potential to do so.

Perhaps more importantly, there will soon be a need for a space-based coronagraph. The ageing SOHO/Lasco and STEREO/Cor 2 are still being relied upon and there is currently no planned mission with a coronagraph that could provide continued monitoring of the corona. Such an instrument is relied upon, not only by the science community, but also by the international forecasting agencies who exploit the intensity images to provide constraints on the size and direction of CMEs. A low corona (1-2  $R_{\odot}$ ) imaging-spectrometer in combination with a wide FOV ( $>2 R_{\odot}$ ),

white light imager would provide a unique combination to study the initiation and development of dynamics in the low corona and their impact on, and evolution out into, the heliosphere (e.g., [DeForest et al. 2014, 2016](#)).

## REFERENCES

- Belcher, J. W. & Davis, Jr., L. 1971, *J. Geophys. Res.*, 76, 3534
- Bruno, R. & Carbone, V. 2005, *Living Reviews in Solar Physics*, 2, 4
- Cranmer, S. R. 2009, *Living Reviews in Solar Physics*, 6, 3
- Cranmer, S. R., van Ballegoijen, A. A., & Edgar, R. J. 2007, *ApJS*, 171, 520
- De Moortel, I., McIntosh, S. W., Threlfall, J., Bethge, C., & Liu, J. 2014, *ApJ*, 782, L34
- DeForest, C. E., Howard, T. A., & McComas, D. J. 2014, *ApJ*, 787, 124
- DeForest, C. E., Matthaeus, W. H., Viall, N. M., & Cranmer, S. R. 2016, *ApJ*, 828, 66
- Evans, R. M., Opher, M., Jatenco-Pereira, V., & Gombosi, T. I. 2009, *ApJ*, 703, 170
- Judge, P. G. 1998, *ApJ*, 500, 1009
- Lee, C. O., Luhmann, J. G., Odstrcil, D., et al. 2009, *Sol. Phys.*, 254, 155
- McIntosh, S. W. & De Pontieu, B. 2012, *ApJ*, 761, 138
- McIntosh, S. W., de Pontieu, B., Carlsson, M., et al. 2011, *Nature*, 475, 477
- Morton, R. J. & McLaughlin, J. A. 2013, *A&A*, 553, 10
- Morton, R. J., Tomczyk, S., & Pinto, R. 2015, *Nature Communications*, 6, 7813
- Morton, R. J., Tomczyk, S., & Pinto, R. 2016, *ApJ*, 828, 89
- Ofman, L. 2010, *Living Reviews in Solar Physics*, 7, 4
- Suzuki, T. K. & Inutsuka, S.-i. 2005, *ApJ*, 632, L49
- Thurgood, J. O., Morton, R. J., & McLaughlin, J. A. 2014, *ApJ*, 790, L2
- Tian, H., Tomczyk, S., McIntosh, S. W., et al. 2013, *Sol. Phys.*, 288, 637
- Tomczyk, S. & McIntosh, S. W. 2009, *ApJ*, 697, 1384
- Tomczyk, S., McIntosh, S. W., Keil, S. L., et al. 2007, *Science*, 317, 1192
- van Doorselaere, T., Nakariakov, V. M., Young, P. R., & Verwichte, E. 2008, *A&A*, 487, L17
- Verth, G., Terradas, J., & Goossens, M. 2010, *ApJ*, 718, L102